AFRL-VA-WP-TP-2006-336

STUDY OF PLASMA ELECTRODE ARRANGEMENTS FOR OPTIMUM LIFT IN A MACH 5 FLOW (POSTPRINT)

J. Menart, S. Stanfield, J. Shang, Roger L. Kimmel, and J. Hayes

JANUARY 2006

Approved for public release; distribution is unlimited.

STINFO COPY

AIR VEHICLES DIRECTORATE
AIR FORCE MATERIEL COMMAND
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542

NOTICE AND SIGNATURE PAGE

AFRL-VA-WP-TP-2006-336 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//
ROGER L. KIMMEL
Senior Research Engineer
Aeroconfiguration Research Branch

//Signature//
CARL P. TILMANN
Acting Chief
Aeroconfiguration Research Branch

*Disseminated copies will show "//signature//" stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
January 2006

2. REPORT TYPE
Conference Paper Postprint

3. DATES COVERED *(From - To)*
01/01/2002– 01/01/2006

4. TITLE AND SUBTITLE
STUDY OF PLASMA ELECTRODE ARRANGEMENTS FOR OPTIMUM LIFT IN A MACH 5 FLOW (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
J. Menart, S. Stanfield, and J. Shang (Wright State University)
Roger L. Kimmel and J. Hayes (AFRL/VAAA)

5d. PROJECT NUMBER
A03U

5e. TASK NUMBER

5f. WORK UNIT NUMBER
0B

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Wright State University
Department of Mechanical and Materials Engineering
Dayton, OH 45435-0001

Aerodynamic Configuration Branch (AFRL/VAAA)
Aeronautical Sciences Division
Air Vehicles Directorate
Air Force Materiel Command, Air Force Research Laboratory
Wright-Patterson Air Force Base, OH 45433-7542

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-VA-WP-TP-2006-336

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Vehicles Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7542

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-VA-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-VA-WP-TP-2006-336

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

Conference paper published in the Proceedings of the AIAA Aerospace Sciences Meeting and Exhibit, published by AIAA. PAO Case Number: AFRL/WS 05-2810 (cleared 21 Dec 2005). Paper contains color.

14. ABSTRACT
This work is an experimental effort to study the power efficiency of using a plasma discharge to alter the lift on a body or surface. In this paper several electrode geometries are considered in an effort to reduce the plasma power required for a given change in lift. The cathode electrode position and electrode size are studied. For all cases studied the anode electrode is kept the same. Results are presented for four different size cathodes and four different cathode positions. The primary result presented is the lift change produced by the discharge per unit power input. The lift is determined by measuring the deflection of the model under the applied plasma. This type of a measurement system has some advantages and disadvantages compared to a load cell lift measurement system used by the authors in past work. Results from each of these lift measurement tools compare well. Results for 9 and 24 mA DC discharges are shown in this paper. For the conditions utilized in this work the results indicate that both cathode position and cathode size affect the lift change caused by a plasma discharge per unit of power input.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	18	Roger L. Kimmel
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

44th AIAA Aerospace Sciences Meeting and Exhibit
January 9 – 12, 2005, Reno, Nevada AIAA 2006-1172

Study of Plasma Electrode Arrangements for Optimum Lift in a Mach 5 Flow

J. Menart[*], S. Stanfield[†], and J. Shang[‡],
Department of Mechanical and Materials Engineering
Wright State University
Dayton, Ohio 45435-0001

R. Kimmel[§] and J. Hayes[**]
Air Force Research Laboratory
Wright Patterson AFB, Dayton, OH 45433

This work is an experimental effort to study the power efficiency of using a plasma discharge to alter the lift on a body or surface. In this paper several electrode geometries are considered in an effort to reduce the plasma power required for a given change in lift. The cathode electrode position and electrode size are studied. For all cases studied the anode electrode is kept the same. Results are presented for four different size cathodes and four different cathode positions. The primary result presented is the lift change produced by the discharge per unit power input. The lift is determined by measuring the deflection of the model under the applied plasma. This type of a measurement system has some advantages and disadvantages compared to a load cell lift measurement system used by the authors in past work. Results from each of these lift measurement tools compare well. Results for 9 and 24 mA DC discharges are shown in this paper. For the conditions utilized in this work the results indicate that both cathode position and cathode size affect the lift change caused by a plasma discharge per unit of power input. For the conditions tested, the lift change is larger when the cathode is placed closer to the leading edge of the plate and when the cathode is larger.

I. Introduction

In 2004 Menart et al.[1] presented results showing how the application of a DC plasma discharge on the top of a flat plate with a half-wedge leading edge effects the lift and drag on the plate. Since the discharge was generated on the top of the plate these investigators showed almost no change in drag because of the application of the plasma, but did show significant changes in lift with the application of the plasma discharge. These investigators recorded an 18% lift change with the application of a 230 watt discharge. This type of a lift change for this amount of power corresponds to a 0.024 gram change in lift for every watt of power input. Because the forces in this work are small the units of grams will be used for lift. These can be changed to newtons by multiplying the gram force by the force of gravity and an appropriate conversion constant. The one thing these investigators did not do is alter the electrode geometry. These investigators always used the electrode geometry and the flat plate model shown in Fig. 1. This work looks at the effects of different electrode geometries and sizes and how they effect the lift change per unit power input.

When starting this work there was good reason to hope that the power consumption per unit input power could be reduced from that obtained by Menart et al.[1], essentially 0.024 grams/watt. Recent work by Menart and Shang[2] with a different electrode configuration indicate that pitot pressure changes of 27% can be realized with a power input of 45 watts. This is a substantial reduction in power input for a measured change in the flow. It must be

[*] *Associate Professor, Member AIAA*
[†] *Ph.D. Candidate, Member AIAA*
[‡] *Research Professor, Fellow AIAA*
[§] *Senior Research Engineer, Associate Fellow AIAA*
[**] *Aerospace Engineer*

realized that a pitot probe pressure change is a local measurement above the surface of the plate and this change was not seen globally throughout the flow above the plate. Most assuredly the lift change will be much smaller than this number. Never-the-less these measurements at least indicate that there is hope for significant changes in lift given a relatively small power input.

While no investigations except Menart et al.[1] could be found that measure total lift changes on a body as a result of applying a plasma, a number of investigators who measure total drag changes caused by a plasma were found. Investigators who made measurements of the total drag on a body in an air flow with the application of a plasma are Leonov et al.,[3] Shang et al.,[4] Toro et al.,[5] Bracken et al.,[6] and Bityurin and Klimov.[7] Leonov et. al. [3] measured the drag on a surface mounted body as a function of plasma input power. These investigators saw drag reductions of 90% at powers of 2500 watts. This is a large amount of power for a relatively small body. Shang et al.[4] measured drag changes on a cylindrical model with a hemispherical nose. The plasma was injected into the Mach 6 flow in a counterflow fashion and seen to alter the drag on the body. Toro et al. [5] used a directed plasma spike, like Shang et al.,[4] but used considerable more power, up to 127 kW, and used a pressure measurement to indicate a change in drag. Bracken et al.[6] measured drag changes on a blunt body with a plasma arc of 13 kW or 30 kW generated upstream of the body. They show a small change in drag with rather large plasma powers. Bityurin and Klimov[7] used a DC discharge and electron beam generated plasma between the wind tunnel nozzle and the model. The DC power was below 500 watts, but the electron beam was using 3 kW of power. These investigators saw large changes in the drag.

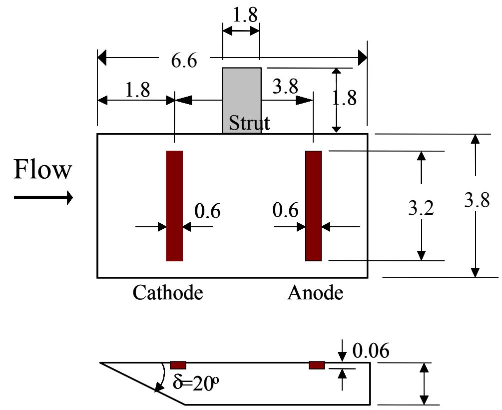


Figure 1. Dimensioned sketch of flat plate model as used by Menart et al.[1] All dimensions are in cm.

All the investigators in the work mentioned above used much larger power inputs to their discharge than what is used in this work. In this work discharge power inputs of less than 30 watts are used. Hopefully larger power inputs will be studied in the future, but this is not the ultimate goal. The goal is to produce large changes in lift with small amounts of power input. One possible means of reducing power input for a given change in lift is to alter the electrode geometry. This is what is studied in this paper. Both the cathode position and the cathode shape are studied. The anode size and position is held constant. In general, the effect of the anode on lift changes relative to the cathode seems to be small. This is a reasonable assumption because most of the energy from the DC discharges being used in this work is deposited in the hypersonic air stream over the cathode. Four different cathode sizes and four different cathode positions are considered. The cathode is always kept upstream of the anode on the surface of a flat plate model with a half-wedge leading edge.

II. Experimental Facility

The nominal Mach 5 wind tunnel used to carry out this work is shown in Fig. 2. The air flow in this figure is from left to right. The test section of the wind tunnel is where the circular window is located. The tunnel is made of acrylic plastic and the undisturbed core of the flow in the test section is about 15 cm high by 3.8 cm in the spanwise direction. A nice attribute of this tunnel is that it can be run continuously at Mach 5. A detailed description of this wind tunnel can be found in Shang et al.[8]

For this work the wind tunnel is run at a stagnation pressure of 370 torr which produces a static pressure of 0.6 torr at the model location. The stagnation temperature of the air entering the wind tunnel varies by as much as 15 K depending on the outdoor air temperature. Typically the stagnation temperature at the inlet to the nozzle of the wind tunnel is 270 K. This stagnation temperature results in a static air temperature of 42 K at the model in the test section.

The model to be used for the lift measurements in this work (see Figs. 3 and 4) is similar to a model used by Menart et. al.[1] for lift and drag measurements in 2004. There are some differences as can be seen by comparing Figs. 1 and 4. The model used in this work is made out of a circuit board. This is the reason the overall thickness of the model is only 0.2 cm. This is compared to the 0.6 cm thick model shown in Fig. 1 which is constructed out of a machineable ceramic. The baseline electrode configuration in the circuit board model can simply be etched out of the 0.03 mm thick copper layer on the upper surface of the circuit board. The electrodes in the model shown in Fig. 1 are made of 0.6 mm thick copper straps. The overall length of the model has been shrunk from 6.6 cm shown in

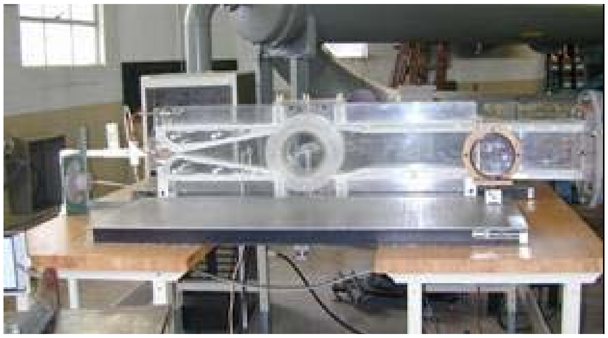


Figure 2. Mach 5 wind tunnel.

Fig. 1 to 5.1 cm shown in Fig. 4. One other difference between the two models is this model has two struts to connect it to the back wall of the tunnel and the one shown in Fig. 1 only had one strut connecting it to four load cells on the back wall of the tunnel.

Menart et al.[1] used the model shown in Fig. 1 to make lift and drag measurements in the wind tunnel shown in Fig. 2. Four load cells were utilized to perform this task. Two were used for making the lift measurement and two were used for making drag measurements. The load cells sense the forces applied to the model as compressive or tensile stresses. These compressive and tensile stresses can be calibrated to determine the lift and drag forces on the model. Since forces are being sensed with this system, the response time is very fast. A difficulty with this type of measurement is that the load cells sometime offer themselves as an alternative path for the plasma discharge. When this happens the load cells are destroyed and new ones must be bought. Since the load cells are expensive this is a problem. This problem was one reason why the lift measurement system used in this paper was devised. Another reason is that a verification of the lift and drag results presented in Menart et al.[1] by a second measurement technique is desired. This will be done in this work.

In this paper a displacement technique for determining the lift on the model is utilized. A given lift force acting in the downward direction will cause the plate to deflect down, and a given lift force in the upward direction will cause the plate to deflect upward. This deflection is proportional to the lift force acting on the plate. A calibration curve of lift to deflection or lift to voltage output from the laser displacement sensor is linear. The deflection of the plate is measured with a Keyance LK-G157 laser displacement sensor. This meter is rated to be able to measure deflections of 0.6 μm. A nice aspect of this measurement is that the displacement meter is located 4.4 inches away from the plasma discharge on the surface of the model in the bottom of the wind tunnel test section out of the high speed flow. This greatly reduces the chances of the plasma passing through the laser displacement sensor instead of between the electrodes. The principle used by the laser displacement sensor to measure the model deflection is by sending out a laser beam that reflects off the bottom of the model to a detector located in the laser displacement sensor. The strength of the reflected laser light from the bottom of the model is proportional to the distance between the laser displacement sensor and the bottom of the model. This detected light intensity is converted to a displacement of the object being interrogated. The sampling frequency of the Keyence LK-G157 laser displacement sensor is 50 kHz. The response time of the model is much slower than this. The natural frequency of the model is 50 Hz. This slow response of the model to deflections is considered a disadvantage of this measurement technique. Having said this, a model with a slow response time tends to eliminate flow noise present in the Mach 5 wind tunnel fro the measurement. The Mach 5 wind tunnel flow noise was sensed by the load cell measurement technique.1

Figure 3. Picture of the flat plate model used in this work.

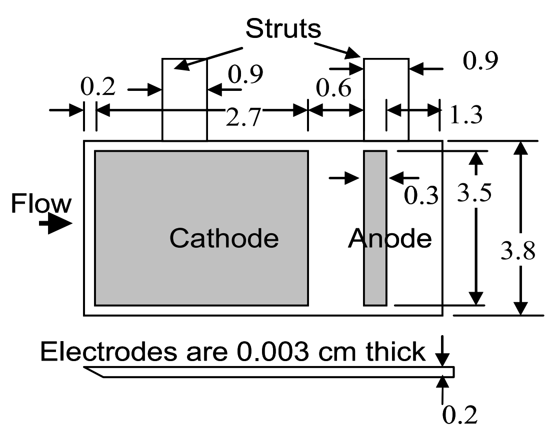


Figure 4. Dimensioned drawing of the flat plate model used in this work.

To take data from the laser displacement sensor a personnel computer, a National Instruments M-Series high speed data acquisition board, and an amplifier is used. All the data in this paper was sampled at a rate of 500 samples per second. In addition to the laser displacement sensor readings the stagnation pressure, stagnation temperature, voltage across the discharge, and current to the discharge are monitored at 500 Hz. To determine the effect of the plasma on the lift, the laser displacement sensor is zeroed just before the plasma is ignited. This way the deflection of the model measured by the laser displacement sensor is only that caused by the plasma. .

The plasma discharges are generated using a Universal Voltronics, unipolar, DC electrical power supply capable of delivering 0.8 amps of current up to electrical potentials of 10,000 volts. This power supply is operated in the current control mode for all the data collected for this paper. In the current controlled mode the power supply automatically adjusts the voltage to deliver a set current. The current output from the power supply is modulated into a 3 Hz square wave by a computer controlled switch that opens and closes at the selected frequency. In this work the square waves have a peak current of 9 or 24 mA. The minimum current in the square wave is zero since this corresponds to an open circuit condition. A low frequency discharge modulation is chosen in this work because of the response time of the model. To obtain a sine wave current profile, used for one set of results shown in the comparison section the DC power supply is computer controlled to give this type of output.

III. Electrode Arrangements

As mentioned in the introduction the primary goal of this work is to check the effect of the lift generated per unit power input for different size cathodes and different locations of the cathode. In this section drawings of all the electrode arrangements studied are presented. For some of the cathode arrangements pictures of the plasma generated with them are given.

To study the effect of size of the cathode the electrode arrangements shown in Figs. 5 and 6 are tested. The difference between these two electrode arrangements is that the cathodes in Fig. 5 start off at the leading edge of the plate and get larger in the downstream direction. Thus all the cathodes shown in Fig. 5 begin at the leading edge of the plate. The cathodes shown in Fig. 6 start off small at a position 2.9 cm downstream of the leading edge and become bigger from this location in the upstream direction. These arrangements of electrodes never completely reach the leading edge. Even for the largest size electrode there is 0.4 cm of nonconducting surface upstream of the leading edge of the cathode. In both of these cases the size of the cathode increases in 0.6 cm increments.

To study the effect of the cathode position the electrode arrangements shown in Fig. 7 and Fig. 8 are tested. The electrodes shown in Fig. 7 are all the same size, 0.6 cm long in the flow direction and 3.5 cm wide in the spanwise direction. Four different positions of this electrode are shown in Fig. 7. Note that the most upstream position is still 0.2 cm downstream of the leading edge of the plate. The cathode arrangement shown in Fig. 8 is essentially the cathodes shown in Fig. 7 rotated 90^o. It should be noted that the long dimension of the electrode was changed from 3.5 cm to 2.7 cm.

All the cathode arrangements shown in this paper were made from the original electrode arrangement shown in Fig. 4. The cathode shown in Fig. 4 simply has to be masked down to obtain any of the arrangements shown in Figs. 5 – 8. This masking process is done with boron nitride paint. This paint is easy to apply and easy to remove. Boron nitride is a good electrical insulator.

IV. Results

Before presenting the results showing the effect of cathode size and cathode position some of the fundamental measured values are presented so the reader can assess the accuracy of the results. A typical lift versus time plot for a 24 mA discharge is shown in Fig. 9. This plot shows the results for a 10 second period using a 3 Hz square wave for the current going to the discharge. The 3 Hz square current wave gives rise to a 3 Hz square power wave. The square power wave is also shown on this plot. The measured lift is the oscillating curve that gradually decreases up to a time of 4 seconds and then oscillates around a constant average value of -0.84 grams. The change in the average value of the lift from 0 to 4 seconds is due to the copper cathode heating to higher temperatures. This same trend occurs when the air flow is removed and the plasma power is oscillated in still air at 7 torr. In this case, however, the 3 Hz oscillations in the lift are not seen. The lift curve is just a smooth change to larger negative values until it levels off to a constant value. Since this average change in lift is seen with the air flow off as well as with it on, it can not be due to the plasma changing the aerodynamic lift forces on the model. The cause of this average change in the lift has to be due to the model heating and deflecting in the downward direction. At this time the authors believe it is due to expansion of the copper cathode relative to the circuit board upon which the copper is attached. It is thought

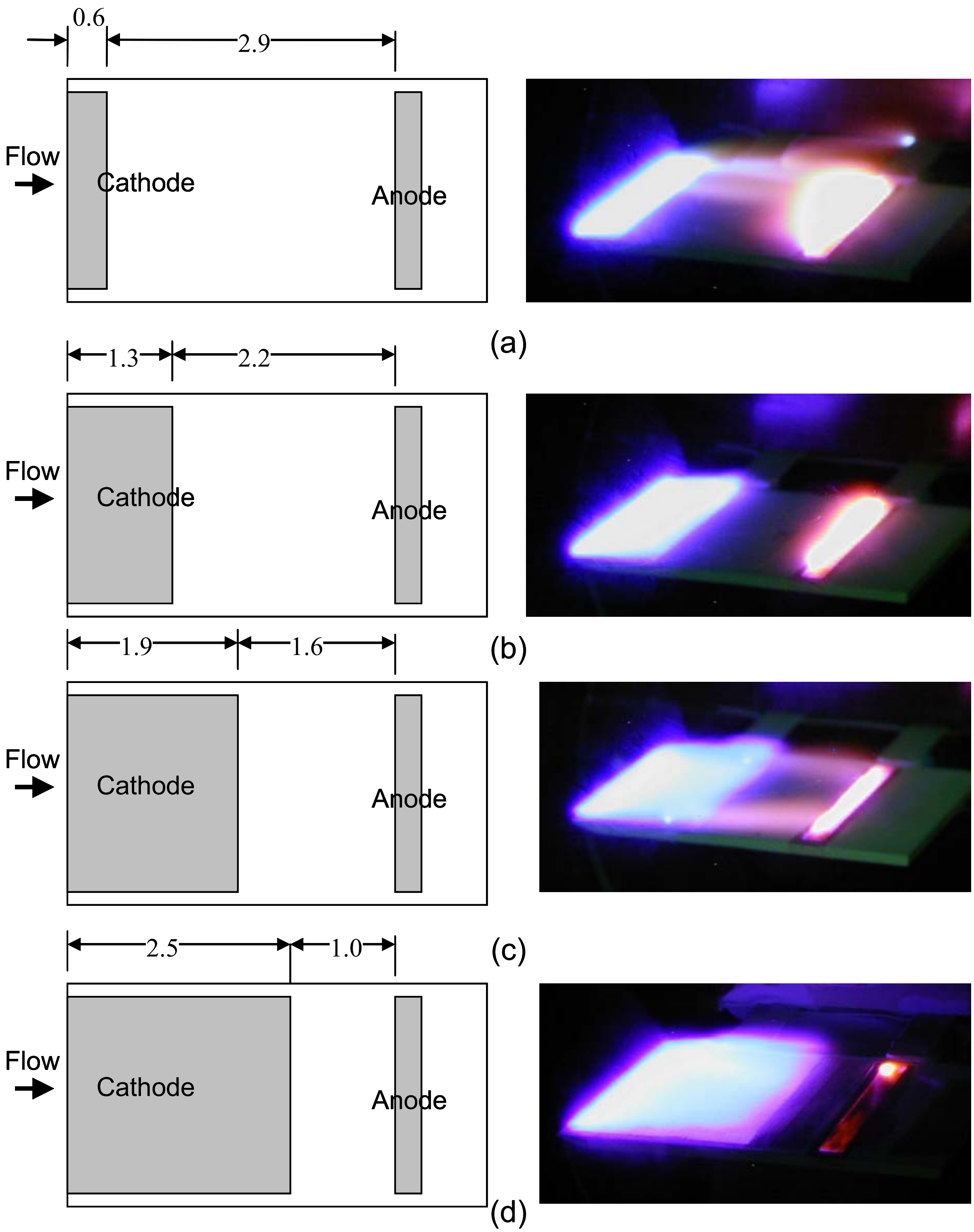


Figure 5. Drawings and discharge pictures of different size electrodes where the cathode becomes bigger in the streamwise direction starting from the leading edge of the model.

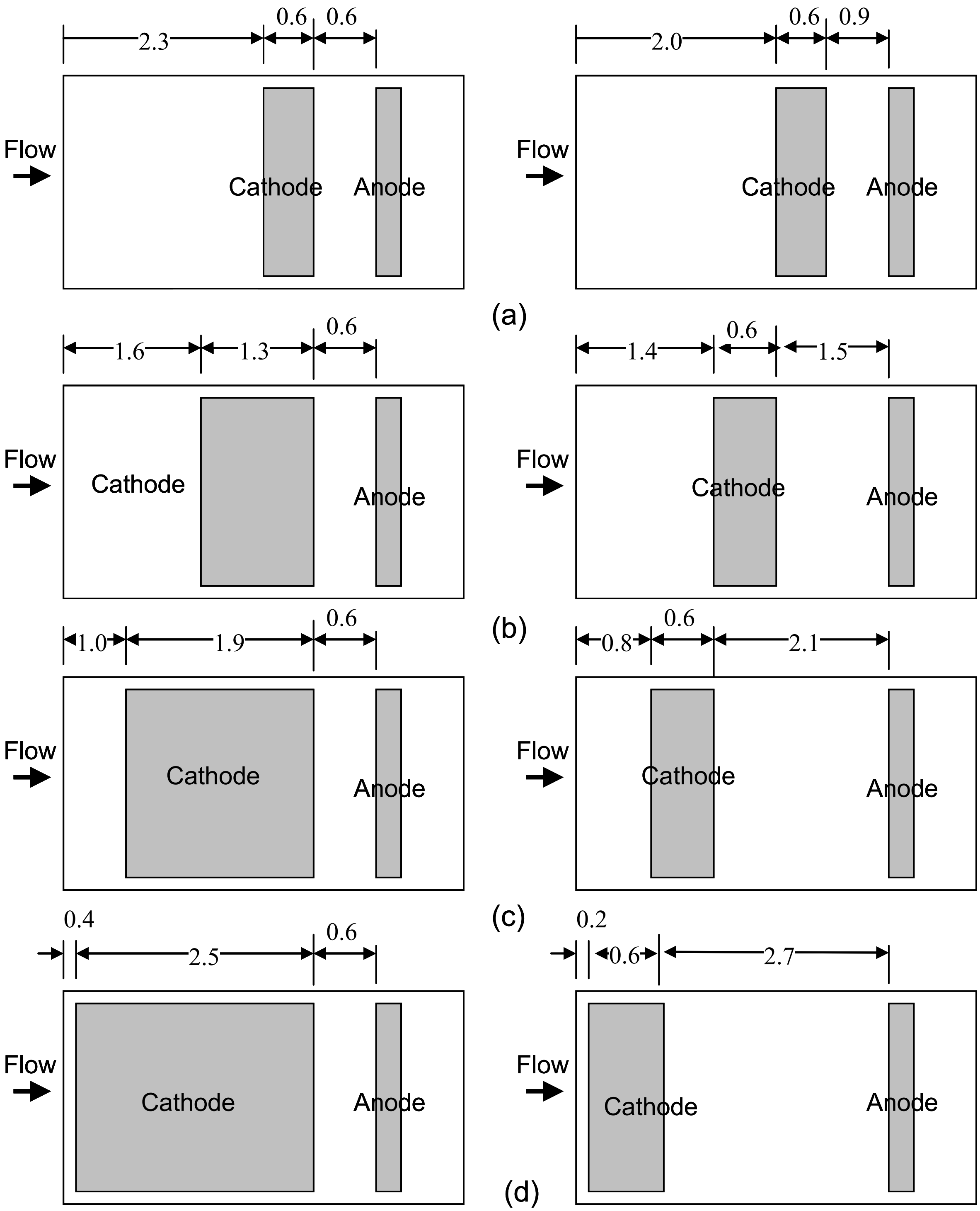
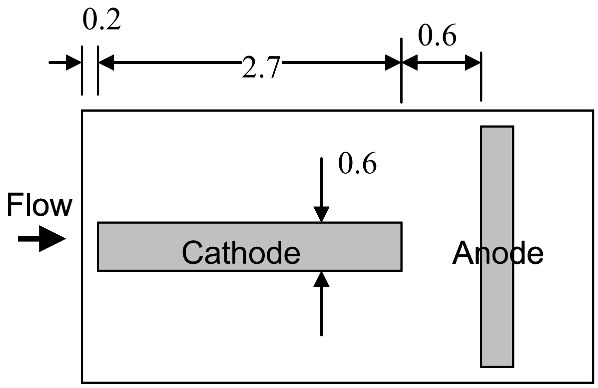


Figure 6. Drawings of different size electrodes where the cathode becomes bigger in the streamwise direction starting from the middle of the model getting bigger in the upstream direction.

Figure 7. Drawings of different electrode positions.



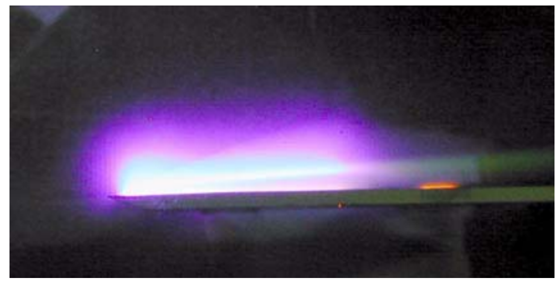


Figure 8. Drawing and discharge picture of streamwise cathode.

that the expansion of the copper bends the model, which is sensed as a change in the position of the model. Every 20 µm displacement of the model corresponds to a 1 gram force. The key aspects of the lift curve that have to be noticed is that the 3 Hz oscillations continue throughout the 10 seconds, these oscillations follow the power input curve, and these oscillations essentially have the same peak-to-peak value for the entire 10 seconds. It is this peak-to-peak value of the lift curve that is the amount of aerodynamic lift caused by the plasma discharge. It is the average of this peak-to-peak value over the last four seconds of the data acquisition period that is presented as the aerodynamic lift caused by the plasma. An enlarged view of the 8 to 10 second results shown in Fig. 9 is given in Fig. 10. In this figure, as well as Fig. 9, there appears to be noise on top of the 3 Hz lift signal. The rapid oscillations seen in the lift results is the model vibrating at its natural frequency of 50 Hz.

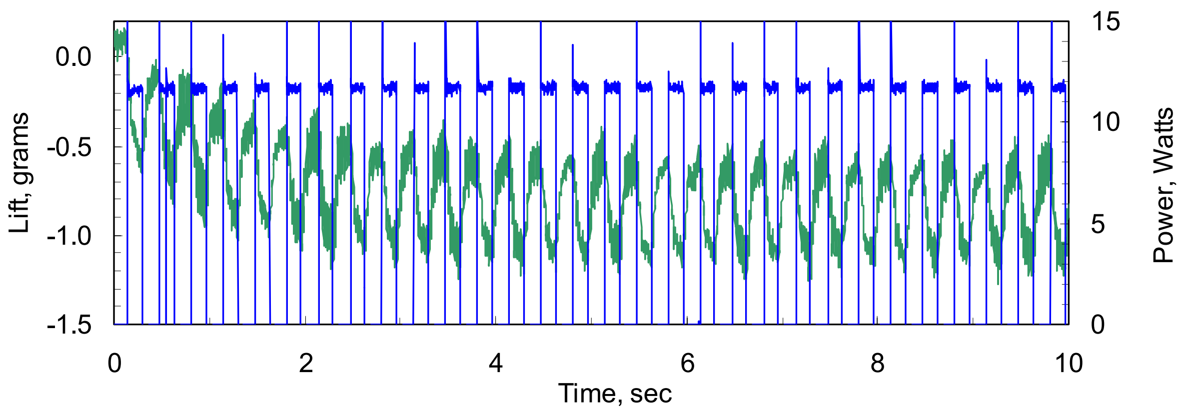


Figure 9. Lift and power versus time for a 24 mA discharge over 10 seconds. The power is the square wave.

The lift and power curves for a modulated 9 mA discharge is shown in Fig. 11. For a 9 mA discharge the lift changes become smaller making it more difficult to extract the aerodynamic lift change caused by the plasma. It can still be done, but the results have a little more uncertainty in them. More scatter will be seen in the 9 mA results then in the 24 mA results.

Another aspect that should be realized about this technique for making lift measurements is that it is sensitive to the location on the plate where the lift is applied. The calibration between model displacement and lift was done at the center of the model. In the streamwise direction a detected lift value can change by as much as 10% depending on where the lift is applied in the streamwise direction. This is an important issue in the results that will be presented. Since the deflection of the plate is a function of the bending moment around a line parallel to the flow direction any movement of the center of lift in the spanwise direction causes substantial changes in the measured lift.

If the center of lift moves from one side of the plate to the other side of the plate in the spanwise direction the measured lift can vary by ±44%. Since all the discharges studied in this work have symmetry around the flow direction axis of the model this should not be a problem.

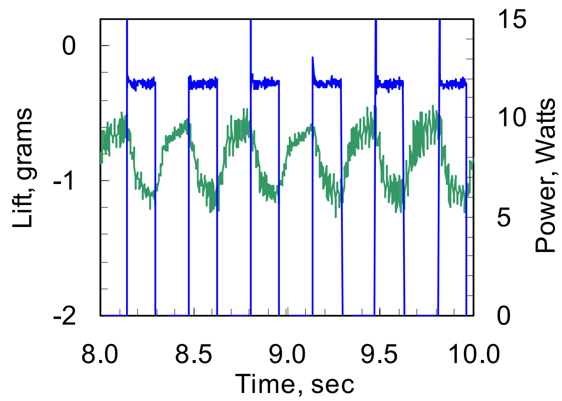


Figure 10. Lift and power versus time for a 24 mA discharge over 2 seconds. The power is the square wave.

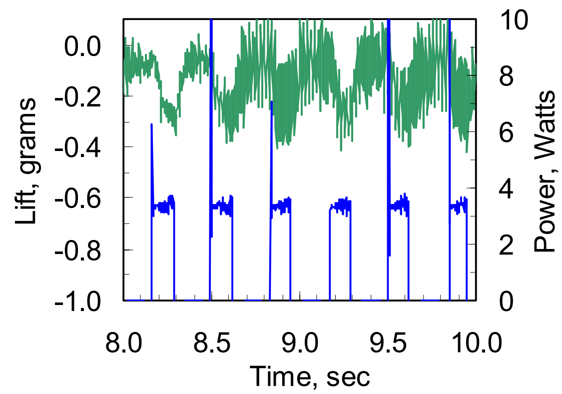


Figure 11. Lift and power versus time for a 9 mA discharge over 2 seconds. The power is the square wave.

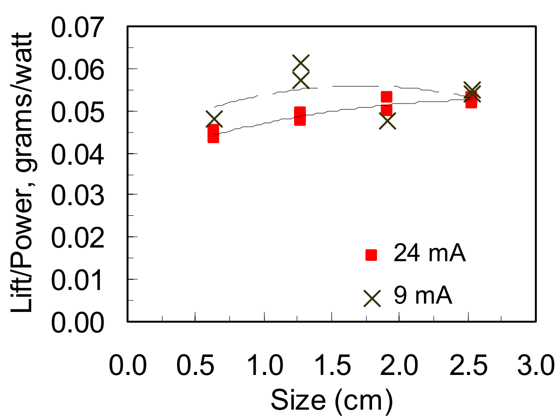


Figure 12. Lift per unit power versus cathode size size where the size of the cathode is increasing from the leading edge of the model downstream. LE and TE in the plot mean leading edge and trailing edge.

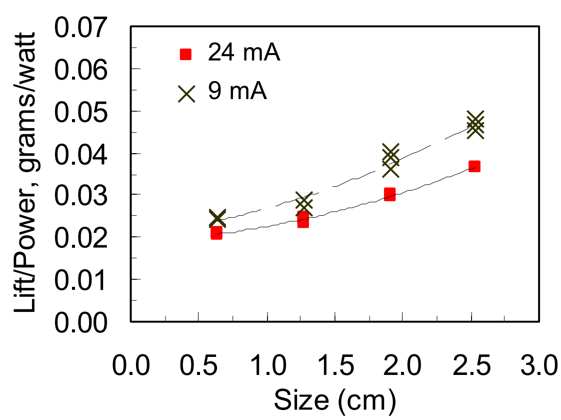


Figure 13. Lift per unit power versus cathode size where the size of the cathode is increasing from the leading edge of the model downstream.

The effect of the electrode size can be seen in Figs. 12 and 13 for a 9 mA discharge and a 24 mA discharge. The results in Fig. 12 are for the cathode sizes shown in Fig. 5 where the cathode increases in size in the downstream direction. The results shown in Fig. 13 are for the cathode sizes shown in Fig. 6 where the cathode increases in size towards the upstream direction. Both of these plots show the lift per unit power increasing as the cathode size increases. This is emphasized by the 2nd order polynomial trend lines placed through the data points. This increasing trend is very clear in the 24 mA results and the 9 mA results in Fig. 13. The trend is not quite as clear in the 9 mA results shown in Fig. 12. These results have scatter to them for the reasons mentioned above. Even with the 9 mA data scatter these results show that the lift per unit power for the 9 mA cases are higher than those for the 24 mA case. It appears that the lift per unit power input is a weak function of the discharge current. This is a rather surprising result. At this time the authors are speculating that this is due to the discharge having slightly different shapes at different currents. The different shapes give rise to heating at different locations.

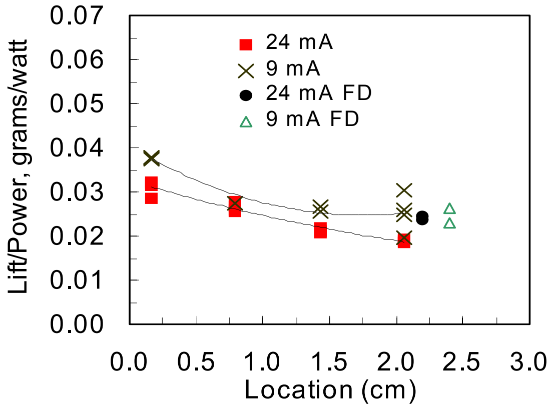


Figure 14. Lift per unit power versus cathode position. FD in the plot means flow direction.

The effect of the cathode position can be seen in Fig.14. These results are for the cathode arrangements shown in Fig. 7. The cathode size remains the same for all the positions shown in Fig. 7, only the location changes. The data points, with the 2nd order polynomial trend line, clearly show the lift per unit power decreasing as the cathode position moves away from the leading edge. A possible reason for this is that the shock is much closer to the surface of the model at the leading edge than distances downstream. For this reason a unit plasma power may be able to affect the flow field at this location more than at a downstream location.

The conclusion that larger changes in the flow field for a given power input are realized at cathode locations closer to the leading edge can be determined from the results in Figs. 12 and 13 also. Noticed that the lift per unit power results in Fig. 12 are larger than those in Fig. 13 for the same size cathode. The cathodes in Fig. 12 are located upstream of their counterpart in Fig. 13. For the 2.5 cm long cathodes, the two values are starting to converge. The Figure 13 value is still a little smaller because this cathode is 0.4 cm downstream of the 2.5 cm cathode in Fig. 12. This can be seen in Fig. 6d and Fig. 5d.

Besides the cathode positions of Fig. 7, the cathode arrangement shown in Fig. 8 is also plotted in Fig. 14. The 24 mA results are plotted at a cathode location of 2.2 cm and the 9 mA results are plotted at a cathode location of 2.4 cm. For this electrode arrangement the cathode position has no meaning, these were just convenient locations to place these results so that they could be compared to the other cathode positions. From these results it might be deduced that placing a cathode with its longest dimension in the spanwise flow direction is better than placing the longest dimension in the flow direction, at least if the spanwise cathode is located close to the leading edge.

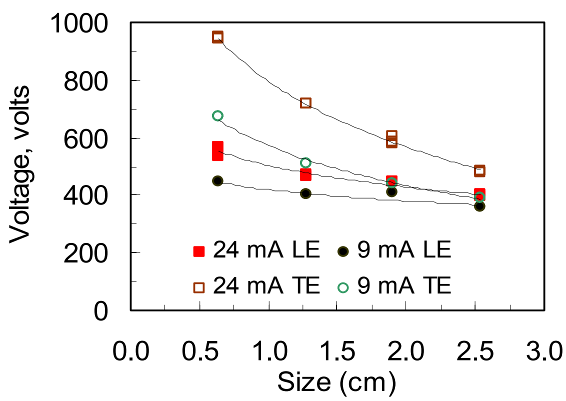


Figure 15. Discharge voltage versus cathode size where the size of the cathode is increasing from the leading edge of the model downstream. LE and TE in the plot mean leading edge and trailing edge.

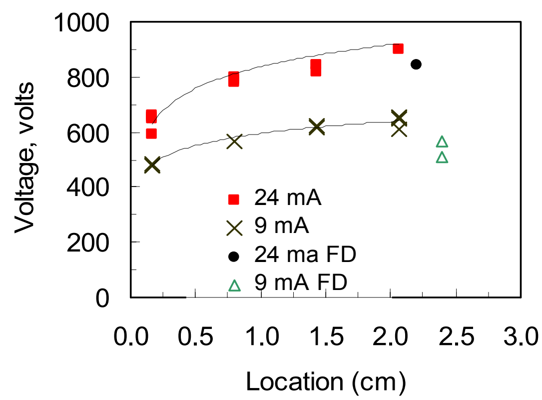


Figure 16. Discharge voltage versus cathode size size where the size of the cathode is increasing from the leading edge of the model downstream.

Another observation made from the measurements made as part of this experimental work is that the discharges are changing when the electrode size or position changes. This can be seen from the discharge voltage plots in Fig. 15 and Fig. 16. Figure 15 results are for varying cathode sizes and Fig. 16 results are for varying cathode positions. Figure 15 shows that the discharge voltage decreases as the electrode size increases. Figure 16 shows that the discharge voltage increases as the cathode position moves away from the leading edge of the model. Increasing voltage with decreasing cathode surface area is an indicator that the discharges being used in this work are not in the normal glow regime. To the eye and from the pictures shown in Figs. 5 and 8 the discharge looks diffuse, and it is

fairly stable. However, these discharges are operating in the abnormal glow mode. Note that both of these figures show that more voltage is required when a 24 ma discharge is used as compared to a 9 mA discharge. This also indicates this is not a normal glow discharge.

V. Comparisons to Prior Lift Measurements

In this section comparisons to the lift results of Menart et al.[1] are made. This is done to verify the results presented in this work utilizing a deflection measurement technique and to verify the results obtained by Menart et al.[1] utilizing a force measurement technique. To do this comparison the linear curve fits of the lift versus power results from Menart et al.[1] and from this work are compared. The equation presented by Menart et al.[1] for the configuration shown in Fig. 1. is

$$L = -0.024P - 0.30 \quad grams \ , \tag{1}$$

where L is the lift in grams and P is the power input in watts. This equation was presented by Menart et al.[1] as a good average curve fit for all the lift measurements they presented. Menart et al.[1] presented 4 of these equations that are slightly different from one another. Equation (1) is the average of these four equations. Lift versus power curves utilizing the displacement measurement device are shown in Figs. 17 and 18. The results in Fig. 17 are for the electrode arrangement shown in Fig. 4. The results shown in Fig. 18 use the electrode arrangement shown in Fig. 7b. the results in Fig. 17 use a sine wave current pulse to run the discharge. The lift versus power equations obtained from both of these electrode configurations are

$$L = -0.026P - 0.041 \quad grams \tag{2}$$

for the results in plotted in Fig. 16 and

$$L = -0.021P - 0.014 \quad grams \tag{3}$$

for the results plotted in Fig. 17.

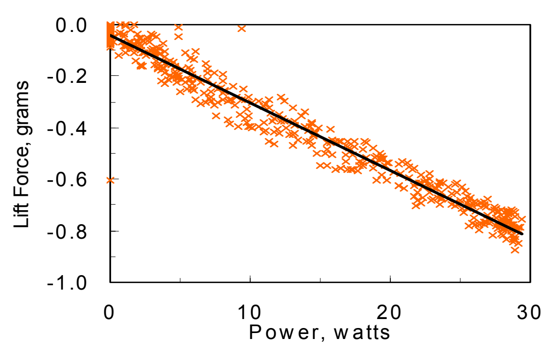


Figure 16. Lift versus power using the electrode arrangement shown in Figure 4 and using a sine wave current input.

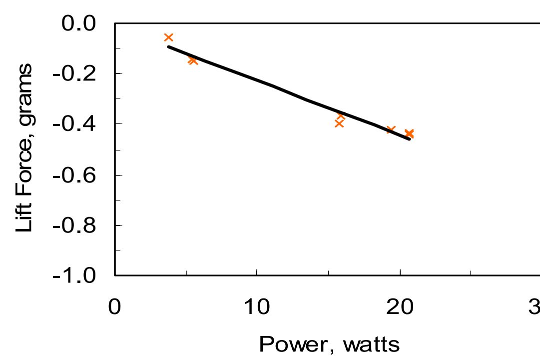


Figure 17. Lift versus power for the electrode arrangement shown in Fig. 7b and a square wave current input.

The slopes in Eqns. (2) and (3) are different from one another because the electrode geometries are different in these two cases. Both of these slopes are slightly different than the one shown in Eqn. (1), but they are within 13%. This indicates that the displacement measurement technique and the force measurement technique used by Menart et al.[1] both give reasonable results. These results also verify what was presented in the previous section of this paper; the electrode geometry does affect the lift to power relationship. The closest electrode arrangement used in this work to that used in Menart et al.[1] is that shown in Fig. 7b. This electrode arrangement is not exactly like that shown in Fig. 1, but it is close. The differences include the spacing between the cathode and anode, the length of the anode in the flow direction and the width of the cathode and anode in the spanwise direction. The biggest difference between

the electrode arrangement shown in Fig. 7b and that shown in Fig. 1 is the spacing between the cathode and anode. The spacing between the cathode and anode used in this work is less than half that used in Menart et al.[1] The length of the anode in the flow direction in this work is half that used in Menart et al.[1] In all the experimental work that we have done utilizing these types of models there has never been any indication that anode size or shape is very important. This is reasonable from an air heating perspective because the discharge does most of its heating above the cathode and a relatively small amount of heating above the anode. The important difference between these two electrode arrangements is probably the distance between the cathode and the anode.

In comparing Eqns. (2) and (3) to Eqn. (1) it will be noticed that the intercept terms in the linear equations are different. If the measurements devices used in this work and the work of Menart et al.[1] were perfectly accurate then the intercept value in all three of these equations should be zero. With no discharge there should be no change in lift. The reason these intercepts occur is because 0.3 grams for the load measurement device and 0.04 grams for the displacement meter are within the measurement accuracy of these devices. Note that Menart et al.[1] measured lifts for much higher input powers, up to 230 watts, while the highest power looked at in this work is 30 watts. An 0.3 g offset is important for the results presented n this work and not so significant for the results presented in Menart et al.[1]

The important comparison to be made here is the slopes. The slopes from Eqns. (2) and (3) obtained using the displacement measurement technique differ by no more than 13% from the slope shown in Eqn. (1) obtained with the force measurement technique. This is a very good comparison and indicates that good results were obtained by Menart et al.[1] and that good results were obtained a part of this work. The 13% difference can easily be explained by the differences in the electrodes.

VI. Conclusions

This work has shown that electrode size and position do affect the lift change caused per unit power delivered by the plasma to the air flow. In general it seems that the most lift per watt of input power is obtained when the discharge is located close to the leading edge of a flat plate body located in a hypersonic flow. It is believed that this occurs because the boundary layer is the thinnest at this location. The experimental results presented here also indicate that larger electrodes provide a better lift to power ratio. For the most part the changes seen by altering the electrode configuration are within a factor of two. In addition to doing an electrode size and position study, a comparison of the results obtained here with a displacement measurement technique to those obtained with a force measurement technique is made. The comparisons indicate that both measurement techniques detect the lift change caused by the plasma discharge well. Both of these lift measurement techniques have their advantages and both of these techniques have their disadvantages.

Acknowledgments

This work was funded through the Air Force Office of Scientific Research, under a laboratory task managed by John Schmisseur. The authors also wish to thank the Air Force Research Laboratory, Air Vehicles Directorate Integration Branch and General Dynamics for their support of laboratory operations.

References

[1]Menart, J., Shang, J., Atzbach, C., Magoteaux, S., Slagel, M., and Bilheimer, B., "Total drag and lift measurements in a Mach 5 flow affected by a plasma discharge and a magnetic field," AIAA 2005-0947, *43rd AIAA Aerospace Science Meeting and Exhibit*, Reno, NV, Jan. 10 – 13, 2005.

[2]Menart, J. and Shang, J., "Investigation of effects caused by a pulsed discharge and a magnetic field in a Mach 5 flow," AIAA 2005-4783, *36th AIAA Plasmadynamics and Lasers Conference*, Toronto, Ontario, Canada, June 6 – 9, 2005.

[3]Leonov, S, Bityurin, V., and Yarantsev, D. "The effect of plasma induced separation," AIAA 2003-3852, *34th AIAA Plasmadynamics and Lasers Conference*, Orlando, FL, June 23-26, 2003.

[4]Shang, J., S., Hayes, J., and Menart, J. "Hypersonic flow over a blunt body with plasma injection," AIAA-2000-2325, *Journal of Spacecraft and Rockets*, vol. 35, pp 367-375, 2002.

[5]Toro, P. G. P., Nagamatsu, H. T., Minucci, M. A. S. and Myrabo, L. N., "Experimental pressure investigation of a "Directed-energy air spike" inlet at Mach 10," AIAA 99-2844, July, 1999.

[6]Bracken, R. M., Myrabo, L. N., Nagamatsu, H. T., Meloney, E. D., and Shneider, M. N., "Experimental investigation of an electric arc air-spike in Mach 10 flow with preliminary drag measurements," AIAA 2001-2734, *32nd AIAA Plasmadynamics and Lasers Conference*, Reno, NV, June 11 – 14, 2001.

[7]Bityurin, V. A. and Klimov, A. I., "Non-thermal plasma aerodynamic effects," AIAA 2005-0978, *43rd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, Jan. 10 – 13, 2005.

[8]Shang, J. S., Kimmel, R., Hayes, J., and Tyler, C., "Performance of a low density hypersonic magneto-aerodynamic facility," AIAA 2003-0329, January 6-9, 2003.